

g_{NKA} AND $g_{NK\Sigma}$ FROM QCD SUM RULES IN THE $\gamma_5\sigma_{\mu\nu}$ STRUCTUREM.E. Bracco^{1*}, F.S. Navarra^{2†} and M. Nielsen^{2‡}¹*Instituto de Física, Universidade do Estado do Rio de Janeiro
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Abstract

The NKY coupling constant for $Y = \Lambda$ and Σ is evaluated in a QCD sum rule calculation. We study the Borel sum rule for the three point function of one pseudoscalar one nucleon and one hyperon current up to order six in the operator product expansion. The Borel transform is performed with respect to the nucleon and hyperon momenta, which are taken to be equal. We discuss and extend the result of a previous analysis in the $\not{q}i\gamma_5$ structure and compare it with the result obtained with the use of the $\gamma_5\sigma_{\mu\nu}$ structure. We find that the effect of pole-continuum transitions is very important in the $\not{q}i\gamma_5$ structure and that it changes completely results obtained in previous analysis. PACS numbers 13.75.Gx, 12.38.Lg, 11.55.Hx

Since already long time ago QCD sum rules (QCDSR) [1] have been used to determine hadronic coupling constants. The most studied case is the pion-nucleon coupling [2–6]. In Ref. [2] this coupling constant was calculated using two different approaches, one based on the three-point function (three interpolating fields sandwiched between vacuum states), and one based on the two-point function (two interpolating nucleon fields sandwiched between the vacuum and the pion states). In both calculations the continuum contributions were neglected. In Ref. [3] the two-point function calculation of Ref. [2] was improved by including higher order terms in the operator product expansion (OPE) as well as a perturbative estimate of continuum contributions, but the soft-pion limit was kept. More recently, Birse and

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Krippa [4] considered the two-point correlator beyond the soft-pion limit and they included also the single pole contribution associated with the transition $N \rightarrow N^*$ [7]. However, in Refs. [5,6], it was pointed out that there is a coupling scheme dependence (dependence on how one models the phenomenological side either using a pseudoscalar (PS) or pseudovector (PV) coupling scheme) in the previous calculations. In order to avoid this scheme dependence the $\gamma_5 \sigma_{\mu\nu}$ Dirac structure was considered. In this structure, the phenomenological side has a common double pole structure, independent of the PS or PV coupling schemes.

There are also works addressing strange couplings, like g_{NKA} , g_{NKS} , $g_{\pi\Lambda\Sigma}$ and $g_{K\Sigma\Xi}$ [8,9] and the charm coupling $g_{ND\Lambda_c}$ [10], all of them based on the three-point function. In this work we shall revisit the calculation of the coupling constant g_{NKY} in the framework of QCD sum rules (QCDSR) considering the Dirac structure suggested in [5,6].

In order to calculate the NKY coupling constant using the QCDSR we consider the three-point function

$$A(p, p', q) = \int d^4x d^4y \langle 0 | T \{ \eta_Y(x) j_5(y) \bar{\eta}_N(0) \} | 0 \rangle e^{ip'x} e^{-iqy} , \quad (1)$$

constructed with two baryon currents, η_Y and η_N , for hyperon and the nucleon respectively, and the pseudoscalar meson K current, j_5 , given by [2,8,11–13]

$$\eta_\Lambda = \sqrt{\frac{2}{3}} \varepsilon_{abc} [(u_a^T C \gamma_\mu s_b) \gamma_5 \gamma^\mu d_c - (d_a^T C \gamma_\mu s_b) \gamma_5 \gamma^\mu u_c] \quad (2)$$

$$\eta_{\Sigma^0} = \sqrt{2} \varepsilon_{abc} [(u_a^T C \gamma_\mu s_b) \gamma_5 \gamma^\mu d_c + (d_a^T C \gamma_\mu s_b) \gamma_5 \gamma^\mu u_c] \quad (3)$$

$$\eta_N = \varepsilon_{abc} (u_a^T C \gamma^\mu u_b) \gamma_5 \gamma_\mu d_c , \quad (4)$$

$$j_5 = \bar{s} i \gamma_5 u , \quad (5)$$

where s , u and d are the strange, up and down quark fields respectively and C is the charge conjugation matrix.

Due to restrictions from Lorentz, parity and charge conjugation invariance the general expression for $A(p, p', q)$ in Eq.(1) has the form

$$\begin{aligned} A(p, p', q) = & F_1(p^2, p'^2, q^2) i \gamma_5 + F_2(p^2, p'^2, q^2) \not{q} i \gamma_5 \\ & + F_3(p^2, p'^2, q^2) \not{P} i \gamma_5 + F_4(p^2, p'^2, q^2) \sigma^{\mu\nu} \gamma_5 q_\mu p'_\nu , \end{aligned} \quad (6)$$

where $q = p' - p$ and $P = (p + p')/2$.

The calculations of the coupling constants based on the three-point function have concentrated on the $\not{q} i \gamma_5$ structure [2,8–10] developing sum rules for F_2 . In the case of $g_{\pi NN}$, Shiomi and Hatsuda [3] considered the $i \gamma_5$ structure whereas Birse and Krippa [4] used the $\not{P} i \gamma_5$ structure. In principle any of these structures can be used to calculate the coupling constant and the sum rules should yield the same result. However, each sum rule could have uncertainties due to the truncation in the OPE side and different contributions from

the continuum. Therefore, depending on the Dirac structure we can obtain different results due to the uncertainties mentioned above. The traditional way to control these uncertainties, and therefore to check the reliability of the sum rule, is to choose the Borel window appropriately (in such a way that the continuum contribution is less than 40 ~ 50%), and evaluate the stability of the result as a function of the Borel mass.

As mentioned before, in Refs. [5,6] it was pointed out that a better determination of $g_{\pi NN}$ can be done with the help of the $\gamma_5 \sigma_{\mu\nu}$ structure, since this structure is independent of the effective models employed in the phenomenological side and it gets a smaller contribution from the single pole term coming from $N \rightarrow N^*$ transition. Motivated by this finding we shall calculate g_{NKY} in this structure and compare our results with previous QCDSR estimates [8,9].

In the phenomenological side the different Dirac structures appearing in Eq.(6) are obtained by the consideration of the Y and N states contribution to the matrix element in Eq. (1):

$$\langle 0 | \eta_Y | Y(p') \rangle \langle Y(p') | j_5 | N(p) \rangle \langle N(p) | \bar{\eta}_N | 0 \rangle , \quad (7)$$

where the matrix element of the pseudoscalar current defines the pseudoscalar form-factor

$$\langle Y(p') | j_5 | N(p) \rangle = g_P(q^2) \bar{u}(p') i \gamma_5 u(p) , \quad (8)$$

where $u(p)$ is a Dirac spinor and $g_P(q^2)$ is related to g_{NDY} through the relation [2]

$$g_P(q^2) = \frac{m_K^2 f_K}{m_q} \frac{g_{NKY}}{q^2 - m_K^2} , \quad (9)$$

where m_K and f_K are the kaon mass and decay constant and m_q is the average of the quark masses: $(m_u + m_s)/2$.

The other matrix elements contained in Eq.(7) are of the form

$$\langle 0 | \eta_Y | Y(p') \rangle = \lambda_Y u(p') \quad (10)$$

$$\langle N(p) | \bar{\eta}_N | 0 \rangle = \lambda_N \bar{u}(p) , \quad (11)$$

where λ_Y and λ_N are the couplings of the currents with the respective hadronic states.

Saturating the correlation function Eq.(1) with Y and N intermediate states, and using Eqs. (7), (8), (9), (10) and (11) we get

$$A^{(phen)}(p, p', q) = \lambda_Y \lambda_N \frac{m_K^2 f_K}{m_q} \frac{g_{NKY}}{q^2 - m_K^2} \frac{(\not{p}' + M_Y)}{p'^2 - M_Y^2} i \gamma_5 \frac{(\not{p} + M_N)}{p^2 - M_N^2} + \text{higher resonances} , \quad (12)$$

which can be rewritten as

$$\begin{aligned} A^{(phen)}(p, p', q) = & \lambda_Y \lambda_N \frac{m_K^2 f_K}{m_q} \frac{g_{NKY}}{q^2 - m_K^2} \frac{1}{p'^2 - M_Y^2} \frac{1}{p^2 - M_N^2} [(M_Y M_N - p \cdot p') i \gamma_5 \\ & + \frac{M_Y + M_N}{2} \not{q} i \gamma_5 - (M_Y - M_N) \not{p} i \gamma_5 - \sigma^{\mu\nu} \gamma_5 q_\mu p'_\nu] + \text{higher resonances} , \end{aligned} \quad (13)$$

where we clearly see all the Dirac structures present in Eq.(6).

We will write a sum rule for the $\sigma^{\mu\nu}\gamma_5 q_\mu p'_\nu$ structure. As we are interested in the value of the coupling constant at $q^2 = 0$, we will make a Borel transform to both $p^2 = p'^2 \rightarrow M^2$. In Eq. (13) higher resonances refers to pole-continuum transitions as well as pure continuum contribution. The pure continuum contribution will be taken into account as usual through the standard form of Ref. [11].

As in any QCD sum rule calculation, our goal is to make a match between the two representations of the correlation function (1) at a certain region of M^2 : the OPE side and the phenomenological side.

In the OPE side only even dimension operators contribute to the $\sigma^{\mu\nu}\gamma_5 q_\mu p'_\nu$ structure, since the dimension of Eq.(1) is four and $q_\mu p'_\nu$ take away two dimensions.

Following Refs. [8,9] we will neglect m_K^2 and m_s^2 in the denominators and, consequently, only terms proportional to $1/q^2$ will contribute to the sum rule.

For the Λ hyperon the diagrams that contribute up to dimension six are shown in Fig. 1. The lowest dimension operator is the mass times the quark condensate with dimension four (Fig. 1a). Since we are neglecting the light quark masses, only terms proportional to $m_s\langle\bar{s}s\rangle$ will appear. This term gives, after a Borel transformation with respect to $P^2 = -p^2 = -p'^2$:

$$[\tilde{F}_4(M^2, q^2)]_a = -\sqrt{\frac{2}{3}} \frac{m_s\langle\bar{s}s\rangle}{16\pi^2} \frac{M^2}{q^2} E_0^\Lambda \quad (14)$$

with $E_0^\Lambda = 1 - e^{-s_\Lambda/M^2}$. In the above equation \tilde{F}_4 stands for the Borel transformation of the amplitude F_4 and s_Λ gives the continuum threshold for Λ .

The next contribution comes from the diagrams involving dimension 6 operators of the type $\langle\bar{q}q\bar{q}q\rangle$ ($\simeq \langle\bar{q}q\rangle^2$) shown in Figs. 1b and 1c. The expressions for these contributions are

$$[\tilde{F}_4(M^2, q^2)]_b = -\frac{4}{3} \sqrt{\frac{2}{3}} \frac{\langle\bar{q}q\rangle^2}{q^2}; \quad (15)$$

and

$$[\tilde{F}_4(M^2, q^2)]_c = -\frac{4}{3} \sqrt{\frac{2}{3}} \frac{\langle\bar{q}q\rangle \langle\bar{s}s\rangle}{q^2}. \quad (16)$$

There would be still another class of contributions to the OPE side related to the four quark processes discussed in Ref. [14]. In Ref. [14] it was shown that four quark processes with nonlocal condensates in the three-point function approach are equivalent to the susceptibilities processes in the two-point formalism [15] and, therefore, should be included when calculating low-momentum transfer processes in the QCD sum rule approach. However, this term does not contribute to the $\sigma^{\mu\nu}\gamma_5 q_\mu p'_\nu$ structure.

The Borel transformation of the phenomenological side gives

$$[\tilde{F}_4(M^2, q^2)]_{phen} = -\lambda_\Lambda \lambda_N \frac{m_K^2 f_K}{m_q} \frac{g_{NKL}}{q^2} \frac{1}{M_\Lambda^2 - M_N^2} (e^{-M_N^2/M^2} - e^{-M_\Lambda^2/M^2}) + \dots, \quad (17)$$

where the dots include now only the contribution from the unknown single pole terms since the pure continuum contribution has already been incorporated in the OPE side, through the factor E_0 in Eq. (14).

For λ_Λ and λ_N we use the values obtained from the respective mass sum rules for the nucleon and for Λ [2,8,11]:

$$|\lambda_N|^2 e^{-M_N^2/M^2} 2(2\pi)^4 = M^6 E_2^N + \frac{4}{3} a^2, \quad (18)$$

$$|\lambda_\Lambda|^2 e^{-M_\Lambda^2/M^2} 2(2\pi)^4 = M^6 E_2^\Lambda + \frac{2}{3} a m_s (1 - 3\gamma) M^2 E_0^\Lambda + b M^2 E_0^\Lambda + \frac{4}{9} a^2 (3 + 4\gamma), \quad (19)$$

where $a = -(2\pi)^2 \langle \bar{q}q \rangle \simeq 0.5 \text{ GeV}^3$, $b = \pi^2 \langle \alpha_s G^2 / \pi \rangle \simeq 0.12 \text{ GeV}^4$ and $\gamma = \langle \bar{q}q \rangle / \langle \bar{s}s \rangle - 1 \simeq -0.2$. In the above expressions $E_2^{\Lambda(N)} = 1 - e^{-s_{\Lambda(N)}/M^2} (1 + s_{\Lambda(N)}/M^2 + s_{\Lambda(N)}^2/(2M^4))$, with s_N being the continuum threshold for the nucleon. The E_i factors in Eqs. (18) and (19) accounts for the continuum contribution.

In order to obtain g_{NKA} we identify Eq. (17) with the sum of Eqs. (14), (15), (16). We obtain [4,6,7]:

$$g_{NKA} + AM^2 = -\sqrt{\frac{2}{3}} \frac{1}{\tilde{\lambda}_\Lambda \tilde{\lambda}_N} \frac{m_q}{m_K^2 f_K} \frac{M_\Lambda^2 - M_N^2}{e^{-M_N^2/M^2} - e^{-M_\Lambda^2/M^2}} a \left[\frac{m_s \gamma}{4} M^2 E_0^\Lambda - \frac{4}{3} a (1 + \gamma) \right], \quad (20)$$

where $\tilde{\lambda}_{N(\Lambda)} = (2\pi)^2 \lambda_{N(\Lambda)}$ and A denotes the contribution from the unknown single pole term coming from $N \rightarrow N^*$ transition which is not suppressed by the Borel transformation [4,6,7]. Using Eqs. (18), (19) we solve Eq. (20) for g_{NKA} by fitting its right hand side (RHS) by a straight line, in the appropriate Borel window. Since Eqs. (18) and (23) determine only the absolute value of λ_N and λ_Λ we can not determine the sign of g_{NKA} .

In this calculation there are some ingredients which are heavily constrained by theoretical or phenomenological analyses. The quark condensate is taken to be $\langle \bar{q}q \rangle = -(0.23)^3 \text{ GeV}^3$. The continuum thresholds appearing in the E_i factors are chosen to be $s_\Lambda = (M_\Lambda + 0.5)^2 \text{ GeV}^2$ and $s_N = (M_N + 0.5)^2 \text{ GeV}^2$. The hadron masses are $M_N = 0.938 \text{ GeV}$, $M_\Lambda = 1.150 \text{ GeV}$ and $m_K = 0.495 \text{ GeV}$. The strange quark mass is taken to be $m_s = 150 \text{ MeV}$ and the kaon decay constant is $f_K = \frac{160}{\sqrt{2}} \text{ MeV} \simeq 113 \text{ MeV}$. The relevant Borel mass here is $M \simeq \frac{M_N + M_\Lambda}{2}$ and we analyse the sum rule in the interval $0.8 \leq M^2 \leq 1.6 \text{ GeV}^2$ where the continuum contribution is always smaller than 50% of the total OPE.

In Fig. 2 we show the RHS of Eq. (20) as a function of the Borel mass squared (thick solid line). We show the results in a broader Borel range than discussed above to show that our conclusions are not very constrained by the Borel window used. To check the sensitivity of our result on the continuum contribution, we have increased the continuum thresholds as: $s_\Lambda = (M_\Lambda + 0.7)^2 \text{ GeV}^2$ and $s_N = (M_N + 0.7)^2 \text{ GeV}^2$, and plotted the corresponding result as the thin line in the same figure. As a first sign it seems that the result is very sensitive to the continuum thresholds. However, as the value of the coupling constant is obtained by the extrapolation of the line to $M^2 = 0$, we immediately see that both curves lead to approximately the same result. Indeed, fitting the QCDSR result to a straight line we get

$$|g_{NK\Lambda}| = 2.37 \pm 0.09 , \quad (21)$$

where the error was only estimated by using the two different thresholds. The value of A is very different in both curves (0.35(−0.26) for the thick(thin) line). However, in both curves it is very small showing that the single pole contribution is not very important in this structure, in agreement with the results in Ref. [6].

As a straightforward extension of our calculation we compute now the coupling constant $g_{NK\Sigma}$ also in the $\gamma_5\sigma_{\mu\nu}$ structure. Phenomenological analyses [16] indicate that this coupling constant should be much smaller than $g_{NK\Lambda}$. Moreover this quantity was also computed in Refs. [8,9] in the $\not{q}\gamma_5$ structure and therefore both results can be compared.

From Eqs. (2) and (3) we see that apart from an overall numerical factor the only difference between η_Λ and η_Σ is the sign change. This sign inversion introduces cancelations and the final number of terms contributing to F_4 in the OPE side is smaller. Moreover, since we take $q^2 \rightarrow 0$ only the diagram of Fig. 1a contributes:

$$\left[\tilde{F}_4(M^2, q^2)\right]_a = \sqrt{2} \frac{m_s \langle \bar{s}s \rangle}{16\pi^2} \frac{M^2}{q^2} E_0^\Sigma \quad (22)$$

The phenomenological side is similar to Eq. (17) with the replacements $\lambda_\Lambda \rightarrow \lambda_\Sigma$, $M_\Lambda \rightarrow M_\Sigma$ and $g_{NK\Lambda} \rightarrow g_{NK\Sigma}$. For the coupling factor λ_Σ we take [2,8]:

$$|\lambda_\Sigma|^2 e^{-M_\Sigma^2/M^2} 2(2\pi)^4 = M^6 E_2^\Sigma - 2am_s(1+\gamma)M^2 E_0^\Sigma + bM^2 E_0^\Sigma + \frac{4}{3}a^2 \quad (23)$$

with the same definitions used before and with $M_\Sigma = 1.189 \text{ GeV}$. The final expression for the sum rule is:

$$g_{NK\Sigma} + BM^2 = \sqrt{2} \frac{1}{\tilde{\lambda}_\Sigma \tilde{\lambda}_N} \frac{m_q}{m_K^2 f_K} \frac{M_\Sigma^2 - M_N^2}{e^{-M_N^2/M^2} - e^{-M_\Sigma^2/M^2}} \frac{am_s \gamma}{4} M^2 E_0^\Sigma . \quad (24)$$

In Fig. 3 we plot the RHS of Eq. (24) as a function of the Borel mass squared for $s_\Sigma = (M_\Sigma + 0.5)^2 \text{ GeV}^2$ and $s_N = (M_N + 0.5)^2 \text{ GeV}^2$ (thick solid line) and for $s_\Sigma = (M_\Sigma + 0.7)^2 \text{ GeV}^2$ and $s_N = (M_N + 0.7)^2 \text{ GeV}^2$ (thin solid line). In this case the sensitivity to the continuum threshold and the contribution from single pole are even smaller. Fitting the QCDSR results to a straight line we get:

$$|g_{NK\Sigma}| = 0.025 \pm 0.015 . \quad (25)$$

The results obtained in [8] are :

$$|g_{NK\Lambda}| = 6.96 \quad \text{and} \quad |g_{NK\Sigma}| = 1.05 . \quad (26)$$

However, the results in Ref. [8] were obtained without considering continuum contribution and they are shown as the dot-dashed lines in Figs. 2 and 3. Once the continuum contribution is included, through the usual E_i factors, the behaviour of the sum rule as a function of the Borel mass changes drastically, as can be seen by the dashed line in Figs. 2 and 3. In particular, both $g_{NK\Lambda}$ and $g_{NK\Sigma}$ become approximately linear functions of M^2 , showing the importance of the pole-continuum contribution in this structure. In Ref. [9] it was found that,

including the continuum contribution in the results of Ref. [8], one obtains $|g_{NK\Lambda}| = 8.34$ and $|g_{NK\Sigma}| = 1.26$. This result is, however, misleading, since the sum rule was not analyzed as a function of the Borel mass, and the single pole contributions were not included.

Fitting the RHS of the sum rule results on the structure $\not{q}i\gamma_5$ [8] (including the continuum contribution) to a straight line one gets

$$|g_{NK\Lambda}| = 1.5 \pm 0.3 \quad \text{and} \quad |g_{NK\Sigma}| = 0.25 \pm 0.05 , \quad (27)$$

where the errors are again evaluated only by considering the two different continuum thresholds.

As in Ref. [6] we find out that we can obtain very different results for the coupling constants depending on the structure considered. Of course the procedure used here to extract the coupling constant (fitting the QCDSR result to a straight line in a given Borel window and extrapolating it to $M^2 = 0$) is more reliable when the single pole term is small. Therefore, the results obtained for the structure $\not{q}i\gamma_5$ may contain big errors since the single pole contribution to this structure is very strong, as can be seen by the dashed lines in Figs. 2 and 3. On the other hand, we may say that the results on the structure $\gamma_5\sigma_{\mu\nu}$, analysed here, are not contaminated by the single pole transitions and its extraction with the method used here is more reliable.

As a final remark we note that the values for the coupling constants obtained here in both structures considered, are not in agreement with the exact SU(3) symmetry. In this limit there are two independent couplings of pseudoscalar mesons too the baryon octet, usually denoted by F and D , corresponding to antisymmetric and symmetric combinations of the octet fields. The SU(3) symmetry, using de Swart's convention [17], predicts

$$\begin{aligned} g_{NK\Lambda} &= -\frac{1}{\sqrt{3}}(3 - 2\alpha_D)g_{\pi NN} , \\ g_{NK\Sigma} &= (2\alpha_D - 1)g_{\pi NN} , \end{aligned} \quad (28)$$

where $\alpha_D = D/(D + F)$. Taking $\alpha_D = 0.64$ [18] we get from Eq. (28): $|g_{NK\Lambda}/g_{NK\Sigma}| = 3.55$. Therefore, our results show a huge breaking of SU(3) symmetry.

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Figure Captions

Fig. 1 Diagrams that contribute to the OPE side for g_{NKY} .

Fig. 2 $g_{NK\Lambda}$ as a function of the squared Borel mass M^2 for the $\gamma_5\sigma_{\mu\nu}$ structure (solid line) and for the $\not{q}\gamma_5$ structure with (dashed line) and without (dot-dashed line) continuum contributions. The thick lines are obtained using the continuum thresholds given by: $s_\Lambda = (M_\Lambda + 0.5)^2 \text{ GeV}^2$ and $s_N = (M_N + 0.5)^2 \text{ GeV}^2$, while for the thin lines lines we used $s_\Lambda = (M_\Lambda + 0.7)^2 \text{ GeV}^2$ and $s_N = (M_N + 0.7)^2 \text{ GeV}^2$.

Fig. 3 Same as Fig. 2 for $g_{NK\Sigma}$.





